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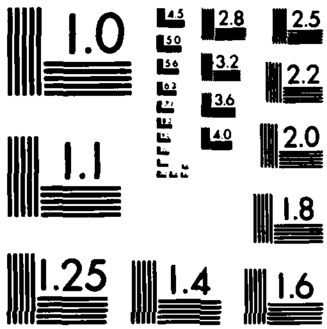
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RESEARCH IN THE OPTICAL SCIENCES

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Research during the fifth year of contract F49620-80-C-0022 is described. Discussed are: optical bistability in thin evaporated films; long-range surface-plasmon polaritons; nonlinear guided wave interactions; theory of two-photon Doppler-free spectroscopy; x-ray image intensifiers with electronic readout; optical bistability; optical bistability experiments to improve solid-state devices and basic understanding; modulated emittance spectroscopy; high-resolution wavefront sensing through the atmosphere; aberrated Gaussian beams; ion beam processing of optical coatings on plastics; optical coatings for

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INTRODUCTION

This report covers the final (fifth) year of contract F49620-80-C-0022, Research in the Optical Sciences. A listing of the many projects addressed during the lifetime of this contract is contained in Appendix A. The results of the investigations have been submitted in semi-annual and final report or appear in theses and dissertations. A complete listing of students who received degrees while receiving support from this contract is given in Appendix B. Titles of the 26 dissertations and 3 theses are also listed. Five students also received support but chose a no-thesis option for their MS degree.

Appendix C lists the many refereed articles, meeting proceedings, and submitted and accepted papers that have resulted from the support of this contract. This impressive 12-page listing represents a significant percentage of the total such output of the Optical Sciences Center.

A SEARCH FOR OPTICAL BISTABILITY IN THIN EVAPORATED FILMS

H. M. Gibbs and H. A. Macleod

BRIEF DESCRIPTION

Room-temperature optical bistability in thin evaporated films of zinc sulphide (ZnS) and zinc selenium (ZnSe) was proposed. In addition, the local nature of increasing absorption optical bistability in color filters was studied.

SUMMARY OF RESULTS

Thin films of ZnS and ZnSe were prepared using the thin film facility of Macleod. Stable optical bistability loops with microsecond switching times and milliwatt switching powers were observed at room temperature. The crosstalk between two adjacent spots on the same device was studied, and it was concluded that thermal conduction does not allow independent operation of spots unless they are $\sim$20 μm apart. We observed longitudinal excitation discontinuities and kinks, arising from partial sample switching in increasing absorption optical bistability, in a color filter.

DESCRIPTION OF WORK DONE

A. ZnS and ZnSe Interference Filters

Interference filters with ZnS or ZnSe as the spacer layer have been the subject of preliminary investigations to assess their potential for optical switching and parallel processing. These thin-film interference filters are very promising for device applications because of their room-temperature operation, extreme thinness (an optical wavelength), ease of production, and low-power operation.

Russian workers reported optical switching in interference filters with switching times as short as a 10 μs and with less than 1 kW/cm^2 switching intensity. They attributed the origin of the optical nonlinearity to a two-photon photorefractive effect. Using a

commercial filter we originally obtained[1,2] switching times of a few milliseconds with about 10 kW/cm^2 of power. The slow switching times (200 μs at best) and the sign of the nonlinearity and the laser-etalon detunings were consistent with a thermal mechanism. However, we have now demonstrated fast, stable switching in a large number of samples at wavelengths from the blue to the red in etalons of ZnS, ZnSe, and Na_3AlF_6 (cryolite).[3-5] The switching times for both turn-on and turn-off are around 10 μs with a few milliwatts of power. There is no sign of deterioration in the films after many thousands of cycles. The crosstalk studies (thermal) for parallel operation suggest that two adjacent spots have to be about 20 μm apart for independent operation.

B. Increasing Absorption Optical Bistability (No External Mirrors) in Color Filters

Recently it was predicted that the local nature of increasing absorption bistability should lead to longitudinal excitation discontinuities, called kinks, which should manifest themselves in sawtooth variations of the transmitted intensity (vs time). Our preliminary results point toward existence of these kinks.[6]

STUDENTS WHO EARNED A DEGREE UNDER THIS PROJECT

G. Olbright, Work toward MS and PhD is in progress

PUBLICATIONS

1. D. A. Weinberger, H. M. Gibbs, C. F. Li, and M. C. Rushford, Annual Meeting of the Optical Society of America, Tucson, Arizona, 1982.

2. M. C. Rushford, H. M. Gibbs, J. L. Jewell, N. Peyghambarian, D. Weinberger, and C. L. Li, "Room temperature thermal optical bistability in thin film interference filters and dye-filled etalons," Optical Bistability II, C. M. Bowden, H. M. Gibbs, and S. L. McCall, eds. (Plenum Press, New York, 1984).

3. H. M. Gibbs, J. L. Jewell, Y. Lee, G. Olbright, S. Ovadia, N. Peyghambarian, M. C. Rushford, M. Warren, and D. A. Weinberger, "Controlling light with light using semiconductor etalons," AVP Specialists Meeting on Optical Circuit Technology, Sept. 11-14, 1984, Munich, West Germany (invited paper).

4. G. R. Olbright, H. M. Gibbs, H. A. Macleod, N. Peyghambarian, and K. Tai, "Low-power microsecond optical bistability in ZnS interference filters," Optical Society of America Annual Meeting, San Diego, California, Oct. 1984.

5. G. R. Olbright, N. Peyghambarian, H. M. Gibbs, H. A. Macleod, and F. Van Millgen, "Microsecond room-temperature optical bistability and crosstalk studies in ZnS and ZnSe interference filters with visible light and milliwatt powers," submitted to Appl. Phys. Lett.

6. H. M. Gibbs, G. R. Olbright, N. Peyghambarian, and H. Hang, "Kinks: longitudinal excitation discontinuities arising from partial sample switching in increasing absorption optical bistability," submitted to Opt. Lett.

LONG-RANGE SURFACE-PLASMON POLARITONS

Dror Sarid

BRIEF DESCRIPTION

During this period the concept and theory of long-range surface-plasmon polaritons propagating on thin metal films and their nonlinear interactions (χ^1, χ^2, and χ^3 effects) were developed. Experimentally, measurements were made, for the first time, of the dispersion of the short- and long-range modes and of the profile of the reflected beam that samples these surface modes.

SUMMARY OF RESULTS

The project is described in detail in the attached list of publications. The main concept of the long-range surface-plasmon polariton has been introduced and discussed in Refs. 1 and 2. It was found that this mode, which propagates along metal films having a thickness in the range of 10 to 100 nm and that are embedded between two similar dielectrics, is accompanied by enhanced electromagnetic fields. These fields can be utilized for nonlinear interactions such as second harmonic generation, four-wave mixing, and magnetic interactions. These theories have been developed in the course of this project (Refs. 8-12) and plans have been made to perform experiments to test these theories. Good agreement was obtained between our theory regarding the dispersion of these modes and experimental results. Two other groups independently tested our original theory (Refs. 1-2) and published their experimental results at the same time as we did. We were also successful in reproducing experimentally the theoretical reflected beam profile. Again, another group tested the theory of Ref. 8 and obtained good agreement with their experimental result, where an enhancement in the harmonic generation was more than two orders of magnitude.

A new concept was recently introduced by us (Refs. 11-12) in which magnetic fields can probe the magnetoplasmon-polaritons at a frequency above the plasma frequency (magnetic modulation spectroscopy).

DESCRIPTION OF WORK DONE

The theoretical metal film thickness-dependent dispersion of short- and long-range surface plasmon polaritons has been calculated for the first time by our group (Ref.1). The theoretical and experimental results are given in Fig. 1. One observes the splitting of the real and imaginary curves as the thickness of the metal film decreases. For the long-range mode, both the real and imaginary components of the propagation constant decrease. Consequently, the mode becomes more evanescent and the range increases. For the short-range mode, the mode becomes more confined in the metal and its range decreases. Agreement between theory and experiment is good, taking into account that the properties of very thin films (10 nm) are not the same as those of the bulk material.

Recent calculations of the profile of the reflected beam on resonance reveal a wealth of data regarding the coupling as well as dissipation and scattering losses. These different mechanisms can be decoupled using computer simulation. An experiment was set up to measure the actual beam profile, and the results are in good agreement with the theory. Shown in Fig. 2 are the theoretical and experimental curves for a 12.5-nm silver film. The agreement between the theoretical and experimental shapes are good, although much work still has to be performed to extract the experimental details from the data.

The optical system used for the experiment is shown in Fig. 3. The light from a HeNe laser is collimated and then is incident on the hemispherical retroreflecting coupler. The reflected beam from the coupler is incident on a high-resolution CCD, using a beam splitter.

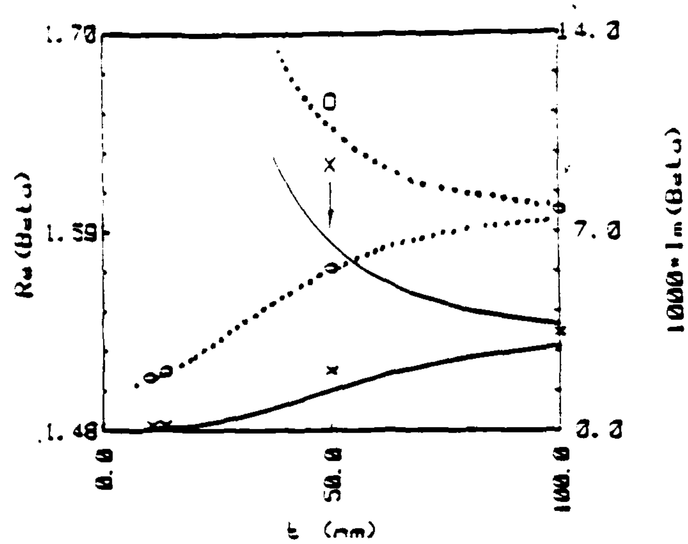


Figure 1. The theoretical results of the real (dotted curve) and the imaginary (solid curve) components of the propagation constant as a function of the metal film thickness τ. The upper and lower branches describe the short- and long-range surface-plasmon polaritons, respectively. The experimental values of the real component of the propagation constant are marked by open ovals. The imaginary component (X) agrees within a factor of 2 with the theoretical results.

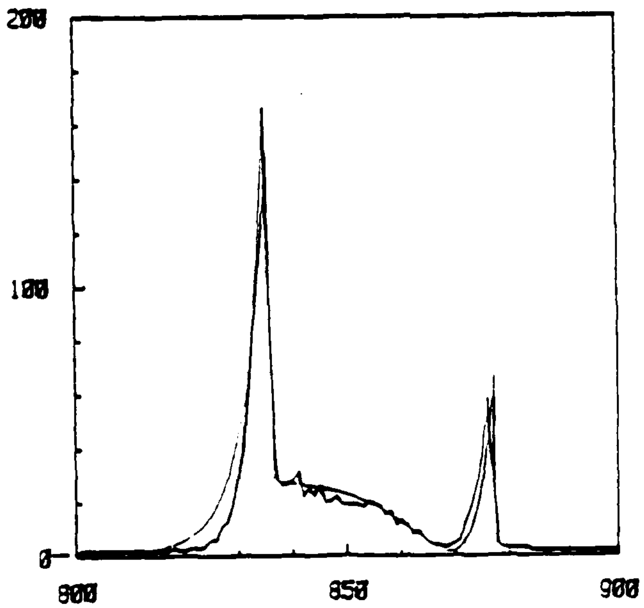


Figure 2. Reflected intensity vs position for square wave input profile. The smooth curve is the theoretical prediction. The other curve was experimentally obtained.

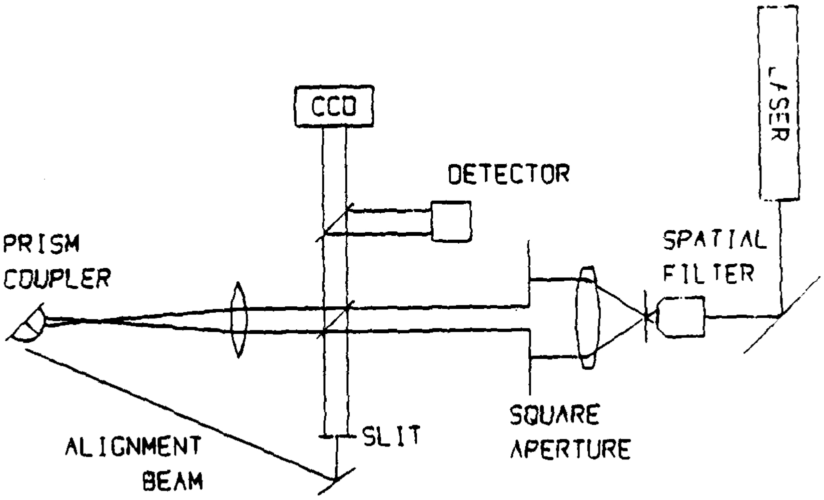


Figure 3. Optical system.

Processing of the CCD output is accomplished by the electronics shown in Fig. 4. The computer controls the angular sweep of the coupler and identifies the absolute value of the zero angle. Then the computer sends a signal to the turntable to rotate until the angle of resonance is reached. At this point the output from the CCD is monitored and plotted. The processing of the beam profile is handled by a software package which extracts the contribution to the beam profile from the various loss mechanisms.

The hemispherical retroreflecting coupler, shown in Fig. 5, consists of a high-refractive-index glass polished into a hemisphere, cut into two, aluminized to obtain the retroreflecting mirror, and then glued back together. The coupler is mounted on a stepping-motor-driven turntable using spring-mounted ball-bearings so that the gap separating the coupler from the thin metal film can be tailored for optimum performance. This gap is filled with index matching fluid which makes it possible to observe separately the short- and long-range modes.

STUDENTS WHO EARNED A DEGREE UNDER THIS PROJECT

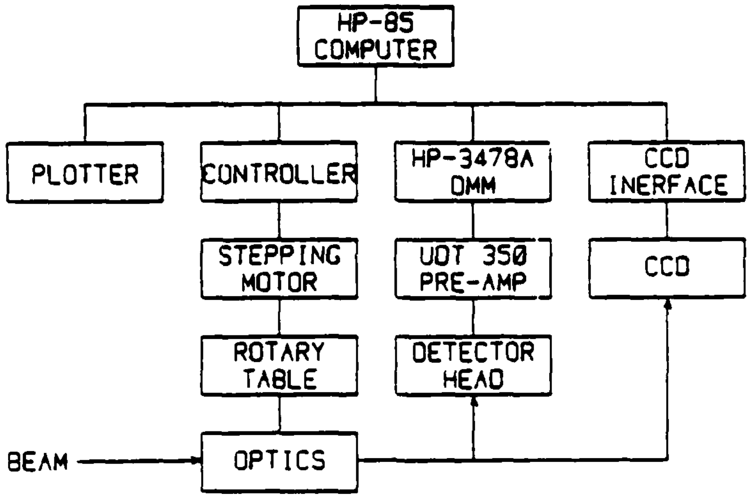
Alan E. Craig, PhD
Title: "Surface Plasmon Waves on Thin Metal Films"

Grieg A. Olson, MS
Title: "Coupling between Finite Electromagnetic Beam and Long-Range Surface-Plasmon Mode"

PUBLICATIONS

1. D. Sarid, "Long-range surface-plasma waves on very thin metal films," Phys. Rev. Lett. **47**, 1927 (1981).

2. D. Sarid, R. T. Deck, A. Craig, R. Hickernell, and R. Jameson, "Optical field enhancement by long-range surface-plasma waves," Appl. Opt. **21**, 3993 (1982).



Figures 4. Computer control schematic.

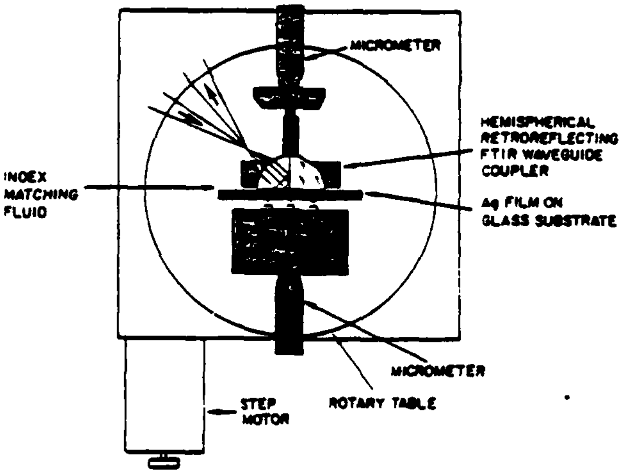


Figure 5. The hemispherical retroreflecting coupler showing the three ball-bearing pressure points for shaping the gap that separates the coupler from the metal film. An index-matching fluid fills the gap and makes it possible to excite the long-range surface-plasmon polariton.

3. A. E. Craig, G. A. Olson, and D. Sarid, "Experimental observation of the long-range surface-plasmon polariton," Opt. Lett. **8**, 380 (1983).

4. D. Sarid, "Long-range surface-plasmon polaritons," in Optics '83: a Report on Emerging Technologies, Optical Society of America (1983).

5. R. T. Deck, D. Sarid, G. A. Olson, and J. M. Elson, "Coupling between finite electromagnetic beam and long-range surface-plasmon mode," Appl. Opt. **22**, 3397 (1983).

6. A. E. Craig, G. A. Olson, and D. Sarid, "Novel system for coupling to surface-plasmon polaritons" submitted.

7. G. A. Olson and D. Sarid, "Experimental observation of the coupling between finite electromagnetic beam and long-range surface-plasmon mode," in preparation.

8. R. T. Deck and D. Sarid, "Enhancement of second harmonic generation by coupling to long-range surface plasmons," J. Opt. Soc. Am. **72**, 1613 (1982).

9. D. Sarid, "The nonlinear propagation constant of a surface plasmon," Appl. Phys. Lett. **39**, 889 (1981).

10. D. Sarid, R. T. Deck, and J. J. Fasano, "Enhanced nonlinearity of the propagation constant of a long-range surface-plasma wave," J. Opt. Soc. Am. **72**, 1345 (1982).

11. D. Sarid, "Enhanced surface-magnetoplasma interactions in a semiconductor," Phys. Rev. B **29**, 2344 (1984).

12. D. Sarid, "Enhanced magnetic interaction of surface-magnetoplasmon polariton," J. Quantum Electronics **QE-20**, 943 (1984).

NONLINEAR GUIDED WAVE INTERACTIONS

George I. Stegeman

BRIEF DESCRIPTION

The goal of this program was to investigate applications of nonlinear integrated optics in various areas of science and technology.

SUMMARY OF RESULTS

The funding obtained from this contract, together with funding from NSF, has been combined to investigate, both theoretically and experimentally, a large number[1-37] of nonlinear phenomena involving waves guided by thin metal and dielectric films. Some of this work has been summarized in review articles.[2,4,6,10,27-30,36,37]

The mixing of two oppositely propagating guided waves was analyzed theoretically and its application to a picosecond transient digitizer was demonstrated experimentally in a titanium in-diffused lithium niobate ($LiNbO_3$) waveguide. It has also been predicted that this process can be used to obtain the electronic spectrum of monolayers deposited on a film surface with large signal levels.

Coherent Anti-Stokes Raman scattering with guided waves has been predicted and verified experimentally to be an efficient technique for obtaining the Raman spectrum of thin films.

Unusual behavior has been predicted when one or both media bounding a guiding film are nonlinear. This includes optical limiter action, regions that are strong candidates for optical bistability and switching, and new waves for both dielectric and metallic guiding films. The optical limiter action was verified experimentally.

The coupling of an external field by a prism into a thin film waveguide characterized by an intensity-dependent refractive index was analyzed and demonstrated experimentally to exhibit optical limiter action.

In addition, degenerate four-wave mixing and its application to all-optical signal processing was treated. Distributed feedback bistability in thin film and channel waveguides has been analyzed theoretically and experiments into the latter are currently under way.

DESCRIPTION OF WORK DONE

(a) Picosecond Transient Digitizer

This work was done in collaboration with Richard Normandin (National Research Council of Canada), a former graduate student.

The process is shown schematically in Fig. 1. When two waveforms of equal frequency overlap in an integrated optics waveguide, a nonlinear polarization is formed that radiates at the sum frequency of the two input beams in a direction orthogonal to the waveguide surface. This interaction is negligible with plane wave fields, but in a waveguide, the strong depth confinement of the guided wave fields leads to a useful signal. If a CCD array is now placed parallel to the waveguide surface, the signal field emanating from each small area along the surface is detected by a corresponding array element and is integrated by that element over the duration of the interaction. The resulting signal now appears as a function of distance along the CCD array. The spatial distribution corresponds to the mathematical convolution of the input waveforms. If one of the input pulses is very short (effectively a δ-function in time), the resulting signal distribution corresponds to the time-envelope of the second pulse. Hence the nomenclature 'picosecond transient digitizer.' This phenomenon is useful for analyzing optical pulses on the time scale of 0.1 to 100 ps.

The convolution of two 16-ps input pulses on a CCD array was demonstrated[1,3] experimentally. A titanium in-diffused waveguide was used and the input pulses were derived from a mode-locked neodymium: yttrium aluminum gallinide (Nd:YAG laser). The resulting signal levels agreed to within a factor of two with calculations and were within the sensitivity range of the CCD array.

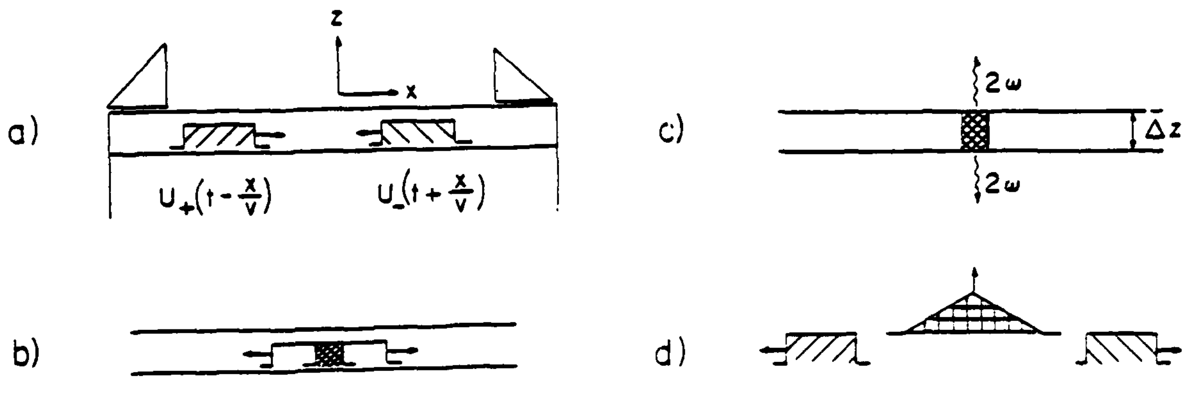


Figure 1. Schematic of the nonlinear mixing of two input waveforms that produces a convolution signal at the harmonic frequency. (a) Two approaching pulse forms in a waveguide. (b) Overlap of the two waveforms at an instant in time. (c) *Radiation by the nonlinar polarization field.* (d) *Convolution waveform* generated by the nonlinear mixing of the (now departing) input pulses.

Calculations were performed[9,12,17,19] for the nonlinear organic MNA and it was predicted that the cross section would be 10^4 larger than for $LiNbO_3$. A single crystal of MNA was grown from super-saturated solution, but not in forms suitable for fabricating waveguides. This was the initial rationale for our interest in the Langmuir-Blodgett (LB) technique for growing nonlinear films. A commercial LB tank has been purchased and, after some delay, is currently being installed.

(b) *Surface and Thin Film Spectroscopy*

The phenomenon of coherent Anti-Stokes Raman scattering involves the mixing of two light beams of frequency ω_1 and ω_2 by means of a material's third order nonlinearity to produce a signal at the frequencies $2\omega_1-\omega_2$, or $2\omega_2-\omega_1$. This process must be phase-matched to be efficient and the phase-matching condition, that is, the relative directions of the two input beams, determines which frequency combination produces a strong signal. If the frequency difference $\omega_1-\omega_2$ is tuned near a vibrational resonance of some of the molecules in the medium being probed, the signal cross section is resonantly enhanced. Thus the Raman spectrum of the medium can be obtained.

We evaluated[15,16] the efficiency of this nonlinear interaction in thin film waveguides and predicted extraordinarily large cross sections both for using the film medium itself as the nonlinear medium (up to 5% conversion efficiencies), and for monolayers deposited on the film surface (10^9 signal photons per laser pulse). This phenomenon should be valuable for determining the concentration and location of contaminants[16] in thin films and for studying the orientation of monolayer molecules bonded onto a film surface.

The initial experiment[16,20] to verify the large signal levels was carried out in collaboration with Bill Hetherington of the Department of Chemistry. The experiment was performed as indicated in Fig. 2. Two beams were coupled into a polystyrene waveguide deposited onto a glass microscope slide so that they would intersect inside the waveguide at

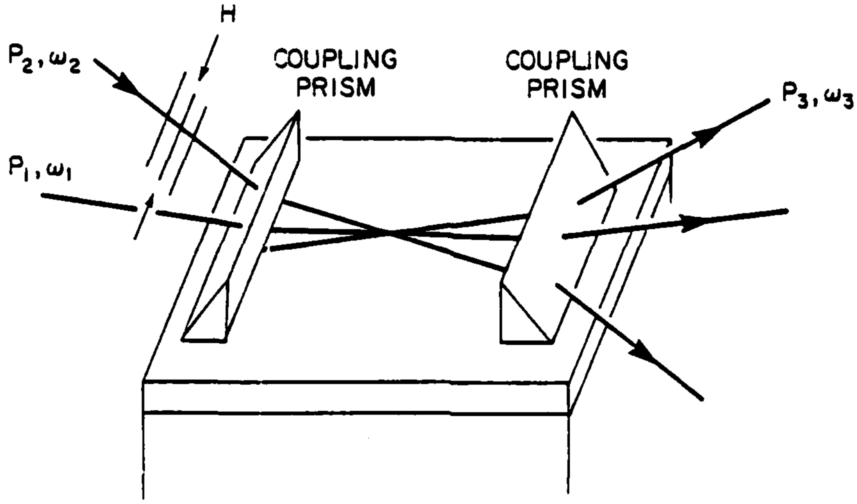


Figure 2. The surface CARS process in a thin film waveguide. The two input beams are coupled into the waveguide through a prism at the frequency $w_3=2w_1-w_2$. The interaction length is the overlap region along the surface. The Raman spectrum is obtained by sweeping the input laser frequency difference w_1-w_2 through the Raman frequencies.

the phase-matching angle. By tuning the frequency difference between the two lasers through the 992 cm^{-1} carbon-hydrogen (C-H) bond of the benzene ring, a maximum signal of 0.2% conversion from pump beam to Raman signal was obtained, in excellent agreement with the calculations.

In fact, in materials such as the highly nonlinear organic PTS, conversion efficiencies of 10's of percent are predicted. This phenomenon could therefore be used for producing a tunable light source.

We have also analyzed[11,13] the mixing of two counter-propagating beams in a thin-film isotropic waveguide with a monolayer deposited on top of it. This geometry was shown previously in Fig. 1. The presence of the film-monolayer interface breaks inversion symmetry and makes the sites for the monolayer non-centrosymmetric. Hence, for input frequencies of ω_1 and ω_2, mixing occurs in the monolayer and produces a radiation field at $\omega_1+\omega_2$ by means of the second-order nonlinearity induced in the monolayer molecules. When $\omega_1+\omega_2$ is tuned through an electronic resonance of the monolayer molecules, the cross section is resonantly enhanced making this interaction a promising tool for probing the electronic spectra of monolayers. Signal levels of $\approx 10^6$ to 10^7 photons (per second for continuous wave experiments and per pulse for pulsed experiments) are predicted.

(c) Nonlinear Guided Waves

The waves guided by a thin dielectric or metal film take on unique characteristics when either the film, one of the bounding media, or both bounding media exhibit refractive indices whose value depends on the local optical intensity. These features become dominant only when the optically induced change in the refractive index becomes comparable to the index difference between the film and one of the bounding media. This problem has been solved analytically by us[22,23,31,32,35] (and others) for nonlinear media bounding both a dielectric and metal film.

Sample results[22] for a single nonlinear bounding medium are shown in Fig. 3a. The effective index governing the guided wave becomes power dependent. Note that for the TE_1 mode there is a maximum power that can be transmitted by the waveguide. For the TE_0 mode, there is also a peak in the transmitted power and, for large changes in the effective index, the wave degenerates into a single-interface surface polariton. Because there is a saturation value associated with the optically induced refractive index change, there is also an absolute maximum associated with the power transmitted by the TE_0 mode, that is, optical limiter action. Similar results are obtained in the metal film case. For two nonlinear bounding media, a host of new wave solutions is obtained with power threshholds, as shown in Fig. 3b. The results are too complicated to be discussed even briefly here, and the interested reader is directed to the published work. In brief summary, optical limiting action, switching, bistability, and optical logic should all be possible based on this phenomenon.

We have observed[26] such anomalous behavior experimentally with a glass waveguide onto which a drop of the liquid crystal MMBA was placed. This material has a large thermal nonlinearity in the blue-green. The transmitted versus incident guided wave power observed is shown for TE_1 in Fig. 4. Note both the saturation in transmitted power and the hysteresis obtained due to the existence of two branches as predicted in Fig. 3a for this case. These results confirm the validity of the theoretical calculations and open up a new spectrum of nonlinear guided wave devices.

(d) Nonlinear Prism Coupler

The efficiency with which radiation can be coupled into a thin film waveguide characterized by an intensity-dependent propagation constant (refractive index) was analyzed theoretically for both prism and grating couplers.[21,34] This type of distributed

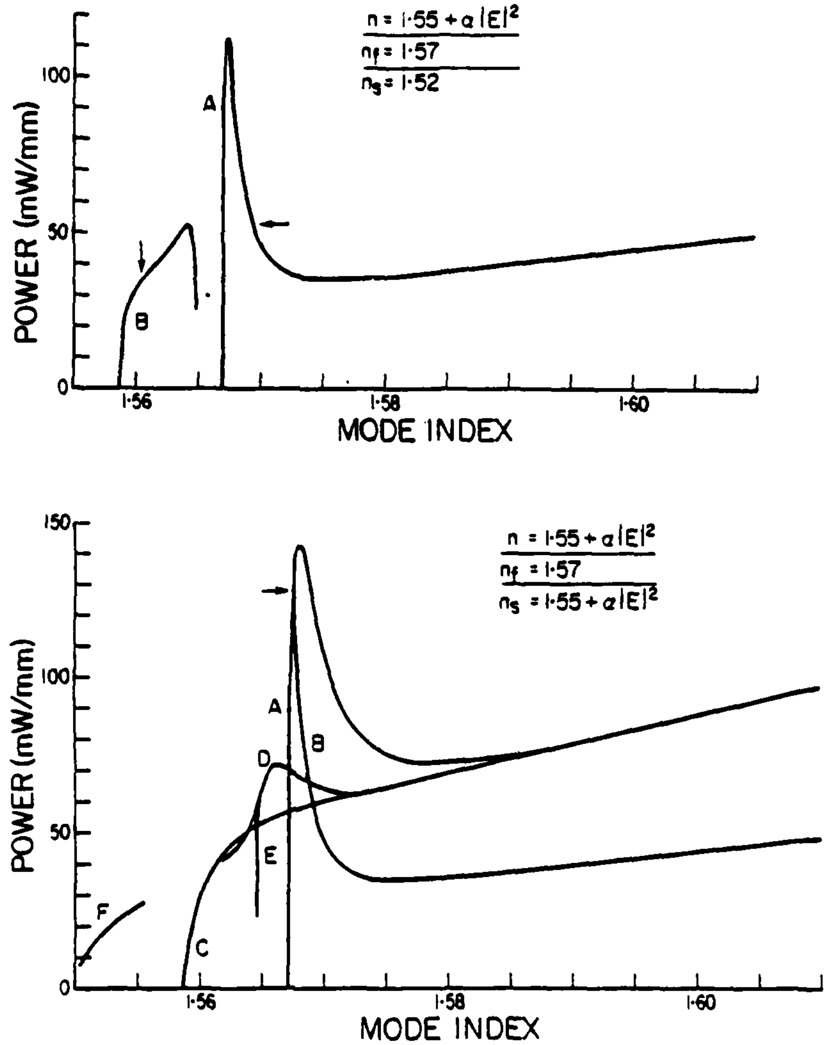


Figure 3. The guided wave power vs effective index for waves guided by a thin film surrounded on one (upper) or both (lower) sides by a self-focussing medium. In the upper diagram A and B correspond to TE_0 and TE_1 waves. In the lower diagram A and B are TE_0 waves, C, D, and E are TE_1 waves, and F is a TE_2 wave, which can exist over a finite power range only.

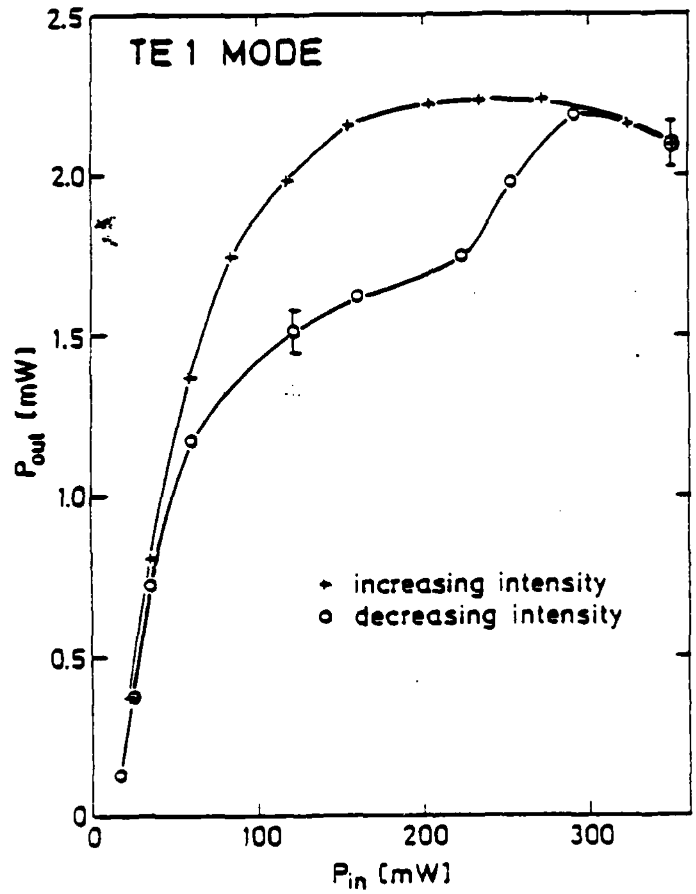


Figure 4. The power transmitted vs incident power for a thin film waveguide with a bead of liquid crystal MBBA on top. Note the power limiting characteristic, as well as the hysteresis, which indicates the existence of two branches for the guided waves.

coupler relies on phase matching along the surface between the incident radiation field and the desired guided wave field. Because the guided wave wave vector changes with the intensity of the guided wave that grows with propagation distance inside the coupler, phase matching is lost and the coupling efficiency decreases. This leads directly to optical limiter action and has important consequences for the amount of power that can be coupled into nonlinear waveguides by means of distributed coupling.

This phenomenon was demonstrated experimentally[33] by placing the nonlinear liquid crystal MBBA beneath a strontium titanate coupling prism and a glass waveguide. As shown in Fig. 5, satauration of the coupling efficiency was obtained. In addition, a number of other predictions of the theory were verified.

(e) Theoretical Analysis of Nonlinear Guided Wave Phenomena

In addition to the theoretical work discussed above, a number of nonlinear guided wave phenomena were analyzed that were not studied experimentally,[8,12,15,17,18,19,23,24] but which together represent a comprehensive treatment of nonlinear guided wave phenomena. In general, we found that the efficiencies of nonlinear interactions using dielectric film guided waves were always far superior to those for metal film guided waves.

The phenomenon of guided wave degenerate four-wave mixing has been analyzed for metal[18] and dielectric waveguides.[24] The salient result is that nonlinear organics such as PTS, which are fabricated by LB techniques, appear promising for efficient four-wave mixing of picosecond pulses. It has also been shown how this phenomenon can be used for signal processing operations[18] such as signal convolution and time inversion, again on a picosecond time scale. Degenerate four-wave mixing in a thin film waveguide, supported under a different contract, has recently been demonstrated.[38]

Bistability with guided waves has also been treated numerically.[3,7,23] In particular it was shown that in thin films of indium antimonide, bistability can occur at power levels of

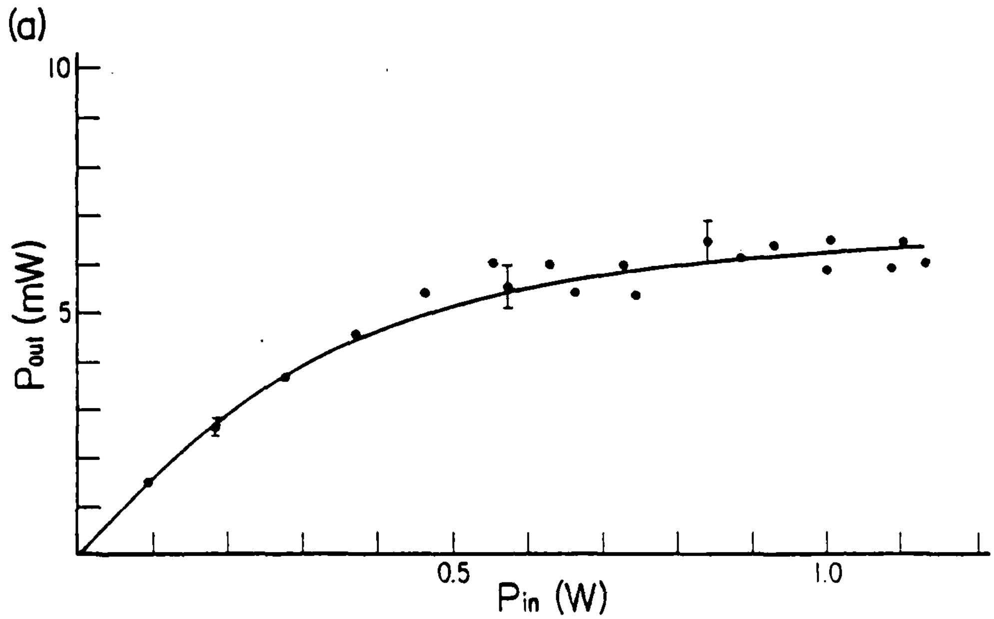


Figure 5. The power coupled into a thin film waveguide vs incident power when the nonlinear liquid crystal MBBA is placed between a coupling prism and a thin film waveguide. Note the limiting action as the coupling efficiency decreases with incident power.

10 μW. In a channel configuration, the power required is only 10 nW. Also promising are the nonlinear organics in which power levels of hundreds of milliwatts are required for distributed feedback channel devices.

PUBLICATIONS

(invited and contributed conference papers not included)

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THEORY OF TWO-PHOTON DOPPLER-FREE SPECTROSCOPY

A. Marathay and M. Sargent III

BRIEF DESCRIPTION

Sargent's theory of probe absorption in continuous-wave (cw) two-photon media subjected to a saturator wave of arbitrary intensity is used to evaluate the accuracy of the popular fourth-order two-photon Doppler-free approximation and to predict the probe absorption outside the limits of this approximation.

SUMMARY OF RESULTS

For low saturator intensities, the standard fourth-order calculations used exclusively to date to treat two-photon Doppler-free spectroscopy are suitable. However, for larger saturator intensities, there are significant deviations from this simple model, even in the extreme Doppler limit.

DESCRIPTION OF WORK DONE

Under earlier JSOP support, Sargent derived the two-photon probe-absorption coefficient for a homogeneously-broadened medium subjected to a saturator wave of arbitrary intensity. This theory has been generalized to allow for Doppler broadening and counterrunning probe and saturator waves. This configuration has been the subject of numerous international meetings during the last 15 years. Integrals over the Doppler distribution have been carried out analytically in a number of limits, such as for extreme Doppler broadening. Numerical calculations have been carried out both in these limits, verifying the computer program, and in intermediate cases beyond the reach of analytic methods. Work continues in investigating our general model numerically, and there are plans to study the wealth of experimental data to find deviations from the simple theory that can check our theory.

X-RAY IMAGE INTENSIFIERS WITH ELECTRONIC READOUT

Eustace Dereniak and Hans Roehrig

BRIEF DESCRIPTION

Conventional x-ray image-intensifier-tube/camera-tube systems are extremely complex. The goal of this project was to reduce this complexity by establishing a direct-electronic-readout image intensifier tube consisting of a photocathode and a micro-channel plate (MCP) similar to those used in conventional imaging tubes but with a charge-coupled-device array in place of the phosphor screen. This approach could lead to x-ray image intensifiers with higher spatial resolution and without lag problems associated with present video-tube related devices.

SUMMARY OF RESULTS

An image intensifying tube has been built using two 32 x 32 (CCD) arrays as the readout. These CCD arrays can survive the fabrication process for image intensifiers and are operable after a 12-hr bake at 250°C. This was a major concern at the beginning of the contract. At the present time the first tube, which was built by Litton Electron Tube Division, is being evaluated.

DESCRIPTION OF WORK DONE

In conventional photoelectronic x-ray imaging systems, the x-ray photons are converted to light photons by the intensifier scintillator. A photocathode in close proximity converts the light photons into photoelectrons that are accelerated to the output phosphor to produce an intensified visible image. This is illustrated in Fig. 1. The visible light is then coupled optically to the video camera, which produces the electronic image.

The initial project design was to replace the output phosphor with a multiwire anode to collect the electrons. The multiwire anode would then be directly connected to a charge-coupled device outside of the image intensifier tube as shown in Fig. 2. By connecting the anode directly to the CCD, the need for optical coupling is then eliminated. For initial testing of the principle, a 32 x 32 CCD array with 100-mm center-to-center spacing was used. To interface the multiwire anode to the CCD, the wires from the anode must have a 32 x 32 array of wires with exactly 100-mm spacing between each wire to watch the CCD spacing. Unfortunately, the multiwire anode available was found to be extremely nonuniform as can be seen in Fig. 3.

As a new approach, the multiwire anode was abandoned and the CCD was placed inside the image intensifier tube. Also, as an initial step to test the principle, it was considered sufficient to use a conventional second-generation low-light-level image intensifier with an input diameter of only 25 mm. A protective mask on the front of the tube with an opening at the location of the CCD ensures that electrons are landing only on the CCD. This new design is shown in Fig. 4.

After the design had been developed, requests for quotation for fabricating two tubes were sent to several tube manufacturers. Litton Electron Tube Division was awarded the contract for the tube fabrication.

To implement the design shown in Fig. 4, the CCD had to withstand temperatures of at least 250°C and preferably 300°C during the tube fabrication. This meant that the CCD had to be tested to see if it could actually withstand the high temperature. This was done by parametically testing a CCD before and after it was baked in a vacuum oven and comparing the data. The results of these tests were positive and the problem of how to power and read the data from the CCD was studied. This was solved by designing a 116-pin header on which four CCD dies were attached; of these, two were bonded for operation as illustrated in Fig. 5.

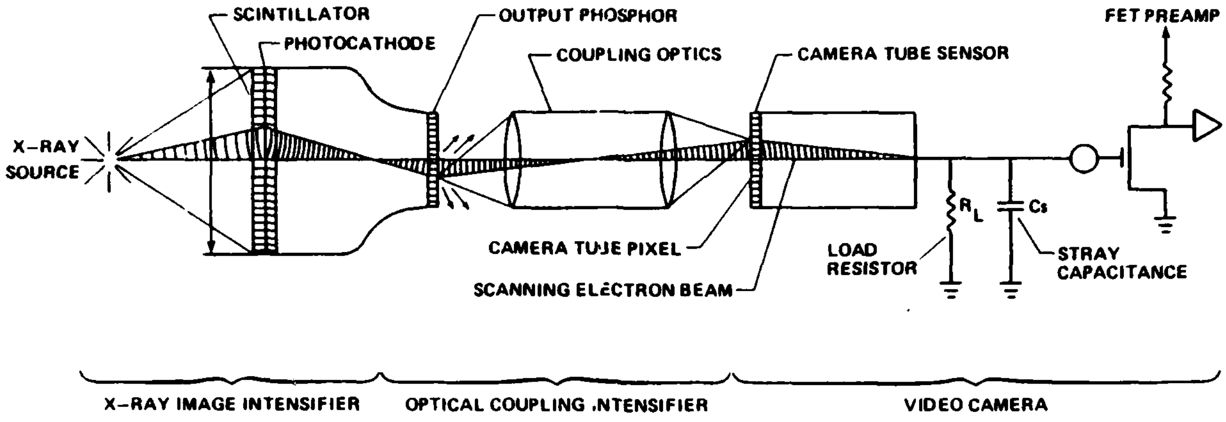

Figure 1. Conventional photoelectronic x-ray imaging system.

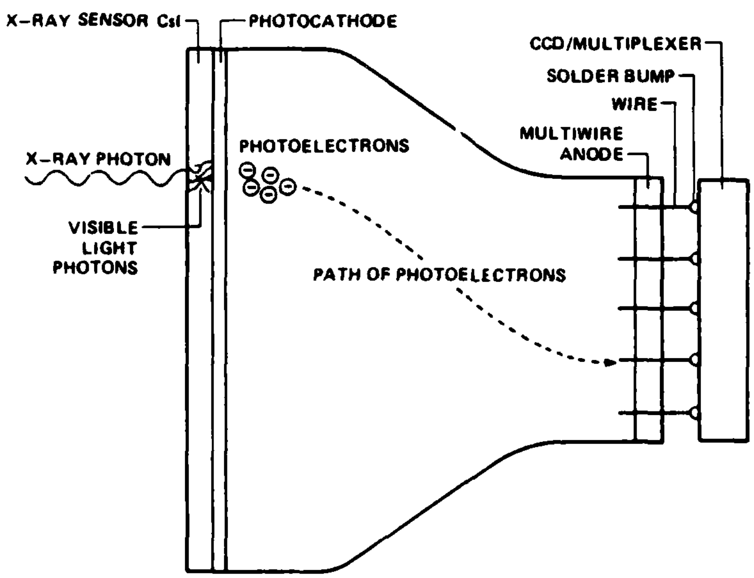

Figure 2. X-ray image intensifier with electrical readout by multiwire anode and CCD array.

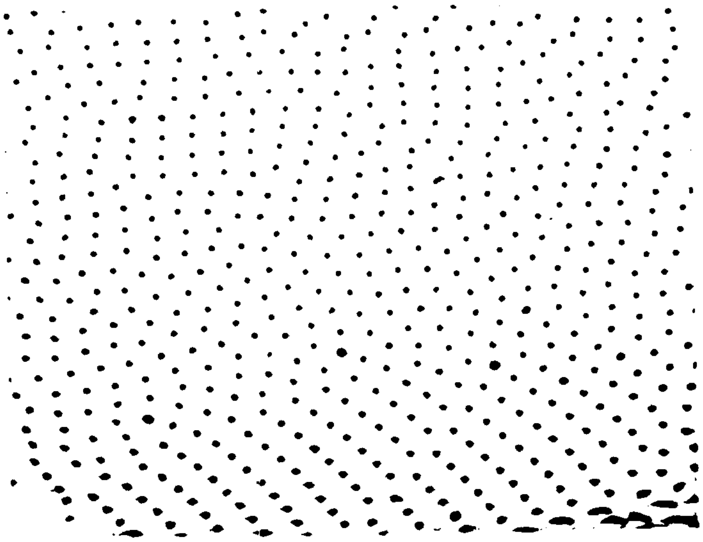

Figure 3. Photograph showing nonuniformity of multiwire anode.

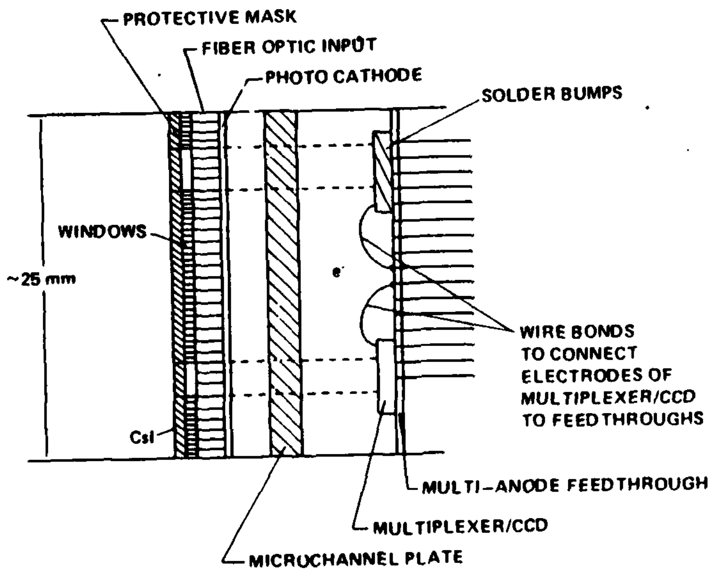

Figure 4. Image intensifier tube.

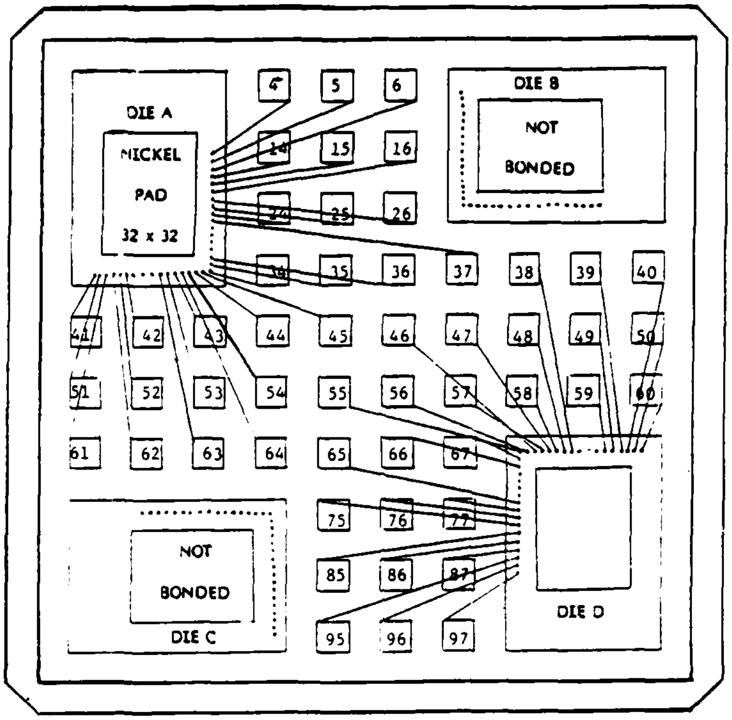

Figure 5. Four CCD arrays mounted on header assembly.

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OPTICAL BISTABILITY

H. M. Gibbs

BRIEF DESCRIPTION

The following goals were undertaken in the study of gallium arsenide (GaAs) optical bistable devices: operation at room temperature, reduction of the switch-on and switch-off times, operation at lower powers, improvement of the flatness of etalons by better etching, understanding of the physics of the operation of the optical bistable device through nonlinear spectroscopy, and investigation of the nonlinear etalons as optical logic gates.

SUMMARY OF RESULTS

We achieved the first room-temperature operation of a bulk GaAs bistable device and demonstrated that the switch-on time is about 1 ps; the switch-off time is still a few nanoseconds. Proton bombardment of the entire etalon did not result in faster switch-off times because of increased thermal effects. Preferential bombardment may alleviate this problem. Flatter surfaces were obtained by introducing extra etch-stop layers on the molecular beam epitaxy (MBE)-grown GaAs materials. We hope that the plasma etching facility that will be available through a DOD grant will provide etalons with better surface quality. The combination of flatter and higher finesse etalons at larger detunings resulted in $\lesssim$ 3-pJ operation of the device in the NOR gate mode. About 500 μW of power were needed for operation at 85 K. Nonlinear spectroscopy of the GaAs material combined with theoretical simulations may bring a better understanding of the exciton saturation and dynamics. Optical logic operations such as AND, OR, NOR were demonstrated both in GaAs and dye etalon devices.

DESCRIPTION OF WORK DONE

A. Room-Temperature Operation

In March 1982 we reported the achievement of room-temperature optical bistability in a gallium arsenide-aluminum gallium arsenide (GaAs-AlGaAs) superlattice etalon.[1-4] This accomplishment greatly facilitated further studies of bistability in the superlattice samples. The removal of the low-temperature dewar resulted in the use of microscope objectives for tight focusing of the laser beam on the etalon. This allowed observation of bistability in bulk GaAs as well.[5-8] Our recent studies show that bistability parameters such as the low switching power and intensity are similar for bulk materials and multiple-quantum-well effects (MQW). Bistability in bulk GaAs may prove to be important because the MBE-grown MQW material is no longer required, and easily available bulk GaAs may be used. However, MQWs might still be needed for providing tunable wavelengths for laser diode operation.

B. Faster Switching Speeds

The switch-on time of a GaAs device depends on how fast the exciton resonance saturates. Our femtosecond studies show that exciton bleaching occurs in $\sim$ 150 fs, limited by the time resolution of the measurement system.[9-11] Since the cavity build-up time is also a few hundred femtoseconds, switch-on time on the order of 1 ps is expected. Our original measurements of switching speed had a time resolution of 200 ps (due to the detector), and consequently 200-ps switch-on times were observed. Recently, we collaborated with a group at the femtosecond facility of ENSTA, Ecole Polytechnique, Palaiseau, France, and measured the speed of a GaAs-AlGaAs device operated in optical NOR gate mode. We obtained a 1-ps gating speed, which suggests that the switch-on time also should be $\sim$1 ps.[13-15]

The switch-off time, $\tau_\downarrow$, at room temperature depends on both carrier lifetime and carrier diffusion time (out of the excited region). Switch-off time of a few nanoseconds has been demonstrated.[16] $\tau_\downarrow$ can be reduced further by proton bombardment of the device, electric field application, or surface recombination. We made preliminary tests of the proton bombardment technique by radiating some of our GaAs wafers (proton bombarding was performed by a collaborator at Bell Laboratories now at Bellcore). Thermal effects dominated the results because the whole sample was radiation damaged. We will preferentially bombard the devices to alleviate this problem.

C. Improving the Flatness of Etalons

Etching techniques have been developed that enable us to consistently obtain etalons flat to one fringe or less. The use of an extra pair of GaAs and AlGaAs etch-stop layers enables improved flatness at each interface.[17-18] Some substrates etch much better than others. Obtaining flat samples will improve greatly the quality of transverse and crosstalk measurements. A sandwich technique in which a flat sample is placed between coated cover slips works well for bistability, thereby avoiding the delay and expense of coating every sample. Preliminary etching with an rf plasma appears to be an even better technique. We have recently obtained a DOD equipment grant to purchase a plasma etching facility that will undoubtedly enhance our capabilities and provide much smoother surfaces.

D. Lower Power Operation

The room-temperature devices are being operated with a few milliwatts of power. The improved etching techniques that resulted in flatter and higher finesse etalons, together with operation farther off resonance to minimize the background absorption, enable us to perform logic operations and calculations with $\lesssim$ 3-pJ incident energy.[19]

At lower temperatures, the background absorption is reduced considerably and the operating frequency can be brought closer to resonance to gain larger index changes. This should result in lower power switching. By cooling the etalons to ∿ 85 K by using a small refrigerator of ∿ 2.5 cm x 7.5 cm size, we obtained 500-μW switching power in a 152 Å MQW device, the lowest power demonstrated in any semiconductor device. The operating wavelength was about 40 Å from the exciton resonance. While the cooling of the etalons might be a nuisance and impractical in commercial applications, it shows that very low power switching is achievable. This project is currently under way.

E. Nonlinear Spectroscopy of GaAs

Experimental and numerical simulations[5,20] of exciton bleaching are under way to help us better understand the physical mechanisms involved and predict optimum conditions for switching. These calculations closely follow the experimental conditions by taking into account factors such as unsaturable background absorption and the nonflatness of etalons.

F. Optical Logic with Nonlinear Etalons

The study of optical logic gates using nonlinear etalons was not proposed last year but was pursued along with our other projects and was demonstrated in dye etalons[21-22] as well as in GaAs [19,23-26] etalons. The output of a "probe" beam, affected by two "input" pulses, defines the logic function. The basic idea is to introduce an initial detuning between the probe frequency and etalon transmission peak such that the presence or absence of input pulses gives a final transmission from the probe that yields the desired logic function. For example, the probe frequency is tuned to the etalon peak for a NOR gate so that the probe output is "high" in the absence of any input. The presence of one or more inputs shifts the etalon peak away from the probe frequency, forcing the probe output to go to a "low" state. We demonstrated that the speed of the GaAs NOR gate device was ∿1 ps, the fastest

speed yet achieved for such a low-power optical logic device. The lowest switching energy has been demonstrated to be < 3 pJ. Attempts to decrease the energy even more are under way.

STUDENTS WHO EARNED A DEGREE UNDER THIS PROJECT

S. S. Tarng, PhD, 1983
Title: "External switching of a GaAs etalon"

J. L. Jewell, PhD, 1984
Title: "Fabrication, investigation and optimization of GaAs optical bistable devices and logic gates"

M. C. Rushford, MS, 1984, No dissertation

S. Ovadia, PhD will be granted in 1984

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OPTICAL BISTABILITY EXPERIMENTS TO IMPROVE SOLID-STATE DEVICES AND BASIC UNDERSTANDING

H. M. Gibbs

BRIEF DESCRIPTION

Room-temperature continuous wave (CW) operation of a bistable gallium arsenide (GaAs) etalon with a laser diode light source, and portable demonstration of optical bistability were proposed. In addition to the proposed work, optical bistability in copper chloride (CuCl) and dye etalons was also studied, and external switching off using two nonlinear etalons was investigated.

SUMMARY OF RESULTS

We achieved the first room-temperature operation of a GaAs bistable device using a laser diode as the only light source. Regenerative pulsations due to thermal effects hindered our original attempts to observe cw operation; however, a diamond heat sink device allowed quasi-cw operation for hundreds of milliseconds. Optical limiting and bistability were observed in CuCl using biexciton resonance. Both switch-on and -off times were subnanosecond detector-limited. Thermal optical bistability in dye-filled etalons was demonstrated. A GaAs device was externally switched off using a second bistable device.

DESCRIPTION OF WORK DONE

A. Room-Temperature Optical Bistability with a Laser Diode

We observed unambiguous optical bistability using a laser diode.[1-5] We matched the laser diode with a 60 Å GaAs multiple-quantum-well (MQW) sample and found that the minimum power for optical bistability was about 6 mW, which is the same as the minimum power level needed when using a dye laser. The laser diode used was a single-mode Hitachi

HLP 1400 that showed reasonably good characteristics. However, there were several problems to be solved.

The first was a mode-hopping problem due to feedback reflection from the focused sample spot to the laser diode. The single-mode laser diode shifts its wavelength, thus changing operating characteristics when mode-hopping occurs. About 0.1 of feedback to the laser diode is sufficient to cause the mode-hopping problem. Even after the laser beam was isolated by using a quarter-wave plate and a polarizer, there was still mode-hopping, which is believed to come from fluorescence and/or scattering of the laser beam at the focused spot at the sample. We reduced this effect by physically moving the sample 2 m away from the source.

The second problem was the power requirement. The maximum power level of commercially available single-mode laser diodes is about 10 mW, but the minimum power required at the sample was 6 mW. Considering the losses from modulators and other optics, usually the actual power on the bistable optical device is less than 50 of the laser diode output power. Actually we overdrove the 12-mW-rated laser diode up to 37 mW to get a bistable loop and then reduced the power to the minimum for optical bistability.

One way to resolve the problem may be to use a thinner sample with higher reflectivity mirrors and thus higher finesse. We plan to try a 76-Å MQW sample with a 0.5-μm GaAs thickness instead of a 66-Å sample with 2-μm GaAs thickness. We expect lower power operation of the bistable optical device from this thinner sample and a new 10-mW laser diode around 850 nm.

B. Portable Demonstration and CW Operation

We demonstrated room-temperature optical bistability using a laser diode at the 1983 meeting of the Optical Society of America. We are not willing to say that it was an easily portable demonstration, in the sense that it was not impressively simple, but the result of the demonstration was successful. For a truly portable demonstration, the source must be a laser diode and the operation should be in a continuous mode, thus eliminating the need for complex electronics.

For cw operation we used diamond mirrors to minimize thermal problems and observed quasi-cw operation (> 100 ms "on") from a 336-Å MQW bistable optical device. We believe the reason for not having true cw optical bistability is due to to occasional large fluctuations in the dye laser intensity occuring on a <1-second time scale caused by bubbles in the dye jet. This problem is not present in laser diodes. By combining diamond mirrors with a thin sample, we should be able to make a better demonstration.

The ultimate goal for the portable demonstration is cw operation of a bistable optical device in which switch-on is fired by a light-emitting diode and switch-off is achieved by blocking the beam. Inexpensive infrared-sensitive cards can convert the output to visible light so that a large group of people can observe bistable operation directly.

C. Optical Bistability in CuCl

Bistability in copper chloride (CuCl) at low temperatures (<77 K) is of interest because picosecond switching operation has been predicted off resonance from the biexciton resonance. We have observed optical limiting and bistability in CuCl films of a few micrometers thickness 90% reflectivity mirrors, and ≈ 10 mW/cm^2 intensity[7-12] in agreement with our calculations, which include excitonic collisions and background absorption from the exciton resonance.[13-15] Switching times were limited by subnanosecond resolution of the detection system. In addition, we investigated the effect

of the local field in the biexciton system and concluded that it does not contribute to mirrorless bistability in reflection.[16,17] Biexciton lasing was observed for the first time in ∿ 1 μm CuCl film.[18,19]

D. Dye Etalon Bistability

Thermal optical bistability has been seen using dye in a solvent between two mirrors.[20] As little as 5 mW is needed, permitting crosstalk studies and control of one beam by another. This system might permit simple two-dimensional array studies.

E. External Switching-Off

External switch-off is achieved using two nonlinear Fabry-Perot etalons in series: the first normally transmits a holding power to the second, which can then be switched on by an external pulse in the usual way.[21] The second can also be switched off by an external pulse that drives the first etalon off its transmission peak long enough for the second to switch off (almost in the dark for fastest switch-off).

STUDENTS WHO EARNED A DEGREE UNDER THIS PROJECT

S. S. Tarng, PhD, 1983
Title: "External Switching of a GaAs Etalon"

J. L. Jewell, PhD, 1984
Title: "Fabrication, Investigation, and Optimization of GaAs Optical Bistable Devices and Logic Gates"

M. C. Rushford, MS, 1984, No dissertation

D. A. Weinberger, PhD, 1984
Title: "Optical Bistability in Thin-Film Interference Filters and CuCl etalons"

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MODULATED EMITTANCE SPECTROSCOPY

B. O. Seraphin

BRIEF DESCRIPTION

In analogy to modulated reflectance spectra, the resonant structure superimposed on the spectral profile of the emittance from a hot surface will be sharply resolved by thermal modulation and suppression of the thermal background. The information will be used to diagnosis the electronic band structure of materials at elevated temperatures.

SUMMARY OF RESULTS

At a given wavelength the radiative power emitted from a hot surface is the product of the spectral emittance of the material multiplied by the Planck function. The first quantity is separately dependent on the temperature and (through the optical constants) on the wavelength. In contrast, the second factor is dependent on the product of wavelength and temperature, and stays constant as long as this product is not varied.

The project rests on the known fact that the optical constants of a material respond in a resonant, sharply profiled spectral structure to the modulation of the temperature of the sample. From there, the modulation is carried over to the optical observables such as reflectance and transmittance. Although never observed before, the resonance structure must be present in the spectral emittance profile, thus opening the diagnostic potential of modulation spectroscopy to the temperature region between room and melting temperature.

The necessary optical equipment has been designed and assembled, and consists of an evacuated sample housing, a spectrophotometer, and detection and modulation equipment. The spectral output from a hot tungsten filament has been measured with high resolution and a discrete profile has been observed in several regions of photon energy. Suppression of the thermal background may clearly resolve the resonant response behind the observed

static structure. Installation of a charge-coupled detector controlled by a computer program, which is in the process of being developed, will complete the experimental setup for the start up of a novel version of modulation spectroscopy.

DESCRIPTION OF WORK DONE

A. Experimental Facilities

The available spectrophotometer was set up and adjusted. A sample holder was designed and built. It holds a filament of the material to be studied clamped between two spring-loaded sleds that maintain constant tension on the sample while its length changes with temperature. The components for the evacuation of the sample chamber were assembled, and flanges and struts for its mounting were designed. The electronics for the modulation of the filament current, the operation of the photomultiplier, and the recorder and microcomputer were installed in a rack.

B. Initial Measurements

The radiative power emitted as a function of wavelength was scanned from a tungsten lamp that was operated at 13 Hz. The intensity modulation superimposed on the output at 13 Hz was recorded, and a small spectral structure was observed at discrete ranges of photon energy. This spectral structure will be studied later once the detection scheme is completed to the point where the modulation of the Planck function can be separated from that of the spectral emittance. The measurements were repeated at different filament temperatures and modulation frequencies. The slight structure stayed at the same photon energy repeatably, indicating the observations relate to the optical properties of the material rather than to the apparatus. Computer hardware and software are being developed to adjust the wavelength scale and to control the effects of temperature modulation on the product of wavelength and temperature. Thus the spectral profile of the

emittance modulation will emerge, resembling the resonant, sharply profiled response known from other versions of modulation spectroscopy.

C. Method of Investigation

The sample to be tested will be mounted in a vacuum chamber where it will be heated electrically. The current will be provided by a high-power programmable power supply connected to a computer programmed to periodically vary the output voltage, thereby varying the sample's temperature.

Light emitted from the sample will pass through a window in the vacuum chamber. It will be focused through a conventional monochromator that has had its output slit replaced by a 1728 element linear CCD array. This will allow a portion of the spectrum to be observed almost simultaneously (limited by the scanning speed of the CCD). The output of the CCD will be processed by circuits that will select three elements from each scan, digitize them to 12-bit resolution, and send them to the computer.

In operation, the computer will set the voltage applied to the sample and select three CCD elements for examination. Two of them will be used to predict the value of the third and the difference between the third and its predicted value will be stored. The voltage applied to the sample will then be changed to change its temperature and three more CCD elements will be selected so that they indicate the same intensity as the previous ones. Again, two will be used to predict the third and the difference will be noted. The results from the experiment will lie in the difference of the differences. Procedures for ensuring that the results obtained are actually temperature effects and not wavelength effects will be applied.

The computer will scan its observations along the CCD, recording the modulation spectrum of the sample. When it reaches the end of the CCD, it will activate a stepper motor coupled to the wavelength drive of the monochromator so that the entire visible and near-infrared spectrum can be explored.

PROGRESS

The computer and the internal circuit boards needed to interface with this experiment have arrived. The programmable power supply for heating the sample has been used in its analog mode for the initial measurements. Only a few cables are needed to connect it to the computer. A special connector required here has been ordered.

The design of most of the CCD readout system is complete and parts have been ordered. Most parts have already arrived and construction has begun. This system is divided into three parts: the power supply is complete; the analog section, which removes the dc offset of the CCD and holds the analog values of the chosen three elements, is almost complete; and the digital section, which synchronizes the system and controls which three pixels the analog board captures, has been started while waiting for parts to finish the analog portion. Documentation of this system is also in progress.

The only part of the CCD system remaining to be designed is the mounting of the CCD array in the monochromator. This is still in the discussion stage. The CCD should be easily removable so that a photomultiplier tube can be used as a check on performance.

The most time-consuming item remaining before preliminary operation can begin is development of the computer program. Coding will probably be in BASIC with an assembly language subroutine for reading the CCD.

Although the stepper motor interface for the computer is on hand, no further thought has been given to this feature. However, preliminary operations can begin without it since the wavelength can be changed manually.

PUBLICATIONS

Since the project started nine months ago, no publications or applications for patents have been generated. Two new students who have arrived for fall semester, 1984 have been tentatively assigned to the project.

HIGH-RESOLUTION WAVEFRONT SENSING THROUGH THE ATMOSPHERE

Chris L. Koliopoulos

BRIEF DESCRIPTION

The ability to measure wavefront distributions with high spatial resolution is necessary for the quantitative analysis of the atmospheric turbulence that occurs over large-aperture astronomical telescopes. The wavefront sensor developed for this purpose can be incorporated in an adaptive optical system for compensation of atmospheric turbulence.

SUMMARY OF RESULTS

This investigation concentrated upon the development of a wavefront sensor that will have certain operational features related to the problem of measuring atmospheric turbulence. Specifically, these are:

a) A large number of detection sub-apertures with a minimal complexity of electronics.

b) The ability to measure wavefront deformations independent of spatial variations in the intensity in the telescope pupil (scintillation). This ability eliminates many interferometric approaches (such as point diffraction and phase contrast) that do not use heterodyne phase detection.

c) The ability to make wavefront measurements using the object itself under observation. The wavefront sensor must therefore perform with white-light extended objects as light sources. This capability also allows horizontal path turbulence measurements by using distant buildings as a structured source.

d) Light-efficient operation with dim stars. This also precludes the use of a direct phase-measuring wavefront sensor.

e) An estimation algorithm able to reconstuct wavefront data from wavefront slope or difference data without bias and with minimal error propagation.

DESCRIPTION OF WORK DONE

The initial work concentrated on the development of an algorithm to reconstruct wavefront slope or difference data (obtained from the wavefront sensor) into wavefront optical path difference (OPD) information over a two-dimensional array. A new algorithm has been developed that minimizes error propagation in the reconstructed wavefront and reduces computation time as compared with other published algorithms. It can be easily implemented in digital electronic hardware. The algorithm is based upon the discrete Fourier transform, which is easily programmable in a computer. Computer simulations have shown exact reconstruction of a wavefront from slope data without noise.

With noise in the wavefront slope data, the reconstruction is optimal in a least squares sense. The dependence of the mean variance of the estimated wavefront on the number of data points becomes a constant for a large number of points. Thus, increasing the number of data points does not lead to a larger variance, unlike a simple reconstruction approach of integrating the slope measurements along a given path.

It is believed that this reconstruction algorithm can be implemented in an adaptive optical system by using commercially available array processor hardware thus reducing the total system cost and the need for specialized hardware.

Studies of these wavefront sensor techniques have concentrated on the incorporation of solid-state integrating detector arrays (such as charge-coupled devices and Reticon photodiode arrays) to allow a large number of data points and serial data manipulation, thus reducing costs. Reticle-based optical systems such as grating lateral shear interferometers are well suited for wavefront sensing with solid-state detector arrays. Difficulties arise when using these types of interferometers to sense wavefront deformations when aberrations may be large. Contrast reduction due to aberration form and magnitude may yield no modulation for a given aberration.

A theory of wavefront sensing using a reticle in the image plane with the detector array in a re-imaged pupil plane has been developed. This theory shows how periodic Fourier filter functions used as reticles may produce unique two-beam interference patterns that can be electronically separated from other unwanted beams. The use of integrating detector arrays, however, limits the type of periodic functions used so that filtering can be done by the detection process. Further work is being done to produce a wavefront sensor reticle function that satisfies the above as well as allowing x-slope and y-slope wavefront information to be obtained from one detector array.

PUBLICATIONS

K. R. Freishclad and C. L. Koliopoulos, "Modal estimation of a wavefront from slope measurements using the discrete Fourier transform," J. Opt. Soc. Am., to be published.

ABERRATED GAUSSIAN BEAMS

R. V. Shack

BRIEF DESCRIPTION

The study of the effects of aberrations on Gau sian beams began with a reexamination of the first-order descriptions of such beams. This study includes both a geometrical model and an unapproximated scalar diffraction analysis. The desire is to obtain a series expansion representation of both the phase and amplitude distributions on which aberrations will be imposed so that the power concentrations in the beam in the near and far field can be determined.

SUMMARY OF RESULTS

The approach to developing an aberration theory for the propagation of Gaussian beams has been twofold. First, a new geometrical model has been developed that provides a simpler and more powerful means of conceptualizing Gaussian beams. This model lends itself well to an aberration theory construct that includes "rays" and fixed reference wavefronts. In addition, the model provides a simple and powerful means of calculating the first-order properties of a Gaussian beam in an optical system. Further, since Gaussian beams are a phenomenon of scalar diffraction theory, a geometrical model alone will not suffice to understand the higher-order terms in a propagating beam. For this purpose, the diffraction problem was reworked by convolving an initial disturbance with the Fourier transform of the transfer function using no approximations and without truncating the beam. The initial disturbance is a plane wavefront with Gaussian amplitude distribution. The convolution will provide a series expansion representation of both amplitude and phase distributions in the beam for the purpose of studying how these change with the imposition of aberrations. This analysis has been successful to date but is not yet complete.

DESCRIPTION OF WORK DONE

A literature search at the beginning of this research revealed that the topic of the effects of aberrations on the propagation of Gaussian beams is a virtually unexplored one. Yoshida and Asakura[1,2] dealt with the value of the Strehl ratio for an off-axis pencil with Gaussian amplitude distribution. A more pertinent paper by Hopkins[3] developed a wave-aberration function for skew rays having a hyperbolic envelope. However, the author assumes the wavefront has a constant amplitude distribution and that the center of curvature of the spherical wavefront is fixed at the waist location, neither of which holds for the Gaussian beam under consideration.

The current first-order description of the Gaussian beam derives from the resonator-mode analysis of Fox and Li.[4] They obtained the steady-state field distribution across the resonator mirrors using the method of successive approximations to numerically evaluate the Rayleigh Sommerfeld diffraction integral with the usual approximation ($R \gg \lambda$). The amplitude distribution for the TEM_{00} mode was found to be Gaussian (within the limits of integration) with the phase surface a constant across the spherical mirrors. This normal or lowest-order mode became the ideal wavefront of a Gaussian beam.

Kogelnik and Li[5] later "derived" a more rigorous mathematical description of the beam. Starting with the scalar wave equation, they postulated a solution having a nonuniform-intensity distribution, a curved wavefront, and a complex phase shift associated with propagation. Characteristic equations for the propagating fundamental mode were established, including the nature of the hyperbolic envelope (locus of constant relative amplitude), the radius of wavefront curvature with distance from the waist, and the phase-shift difference between the Gaussian beam and an ideal plane wave. This description can also be deduced from another method as shown by Kogelnik.[6] Beginning with the

expression for a spherical wave, e^{ikR}/R where $R^2 = x^2 + y^2 + z^2$, the z variable is made complex instead of purely real. The radius R is approximated using the lowest-order term in a binomial expansion and then substituted back into the wave expression. The resultant form is that of the Gaussian beam. This exercise demonstrates that higher-order terms exist not only in the phase distribution but also in amplitude and that both change upon propagation of the "Gaussian" beam.

The first-order description of a beam is the usual starting point for the mathematical treatment of its aberrated terms since aberrations can be properly understood only in relation to ideal wavefronts and their normals or rays. In this case, difficulties arise in attempting to model the beam to include ray-like phenomena and expand wavefronts with a single center of curvature. The locus of constant relative amplitude in a plane containing the axis of propagation describes a hyperbola. Not only is the idea of a curved ray impossible in a homogeneous medium, but a family of spherical surfaces (i.e., wavefronts) is not orthogonal to a family of hyperbolas (i.e., rays). The other problem posed by the model concerns the center of curvature of the expanding wavefronts. This center varies in a nonlinear fashion along the axis with the asymptotic wavefront curvature centered at the waist. Likewise, the radius changes nonlinearly, decreasing to a minimum from the waist and then increasing again. This significantly complicates the development of a wave aberration theory which assumes a reference sphere centered at the geometrical focus and a ray aberration theory for wavefront normals directed to the same point.

The model developed here consists of a skew line rotated about the axis. This process sweeps out a hyperboloid of one sheet, the envelope of a Gaussian beam. If this skew line is projected onto a plane where the axis of propagation is a point, the first-order properties of the beam can be calculated easily.[7] Since the skew line is tangent to the hyperbolic

envelope everywhere, it is the locus of constant amplitude in a plane skewed to the axis of propagation.

Consider a segment of length r of one such skew line with one end point on the plane of the waist and the other in a plane a distance z from the waist. The end points are located at different radii from the axis and with an angular separation α. If the line segment is moved toward the axis in such a way that it maintains contact with both radii joining the axis and the original end points, and maintains a constant length r, it will sweep out an elliptical cap to the plane at z. This elliptical cap is a section of an oblate ellipsoid rotated about the axis of propagation and having the same foci as the hyperboloid. A family of such ellipsoids forms the orthogonal family to the hyperboloid. If this ellipse is considered a wavefront, a skew line lying on the orthogonal hyperboloid between any two "wavefronts" possesses the ray-like property of maintaining a constant optical path length.

The skew line, and therefore the hyperbolic envelope, is easily described by the tangent of the angle it makes with the axis of propagation. This is also the beam divergence angle. Indeed, the radius of curvature of the spherical wavefront in the traditional beam description, R_o, is related to the radius of vertex curvature of the ellipse, R_e, by the cosine of the beam divergence angle, δ, or:

$$R_e \cos\delta = R_o \,.$$

This illustrates the small difference between a spherical wavefront and the postulated ellipse. In most beams, δ is small and the radii of curvature are almost identical. The differences would not be apparent except in very fast beams with large divergence angles. Insights such as these demonstrate the usefulness of the model, which is still being expanded and explored.

In addition to the above, the Gaussian beam as a diffraction problem has been reconsidered from a different perspective than the traditional approach. The field distribution in a plane a distance z from an initial disturbance is the convolution of the initial disturbance with the Fourier transform of the transfer function, $e^{ik\gamma z}$. This transform can be expressed in many forms, including the traditional Green's function of the Rayleigh Sommerfeld integral:

$$2\pi \left[\frac{\hat{z}}{\hat{r}}\right] \left[\frac{1}{2\pi\hat{r}} - i\right] \frac{e^{i2\pi\hat{r}}}{2\pi\hat{r}}, \quad \hat{r} = \frac{r}{\lambda}, \quad \hat{z} = \frac{z}{\lambda}.$$

If the usual assumption is made that $r \gg \lambda$, this becomes

$$-i\left[\frac{\hat{z}}{\hat{r}}\right] \frac{e^{i2\pi\hat{r}}}{\hat{r}}.$$

The term $\hat{z}/\hat{r}$ is the obliquity factor. As shown by Shack,[8] making the approximation this way eliminates not only the evanescent components but some of the propagating terms as well. The effect is somewhat akin to approximating an integrand containing derivatives of functions by the functions themselves. At the very least, an unapproximated analysis would permit an estimation of the amount of error introduced by the absence of these terms. We hope it will also provide much useful insight into both the "ideal" wavefront (lowest-order term) and higher-order terms.

The kernel of the diffraction integral can also be written in terms of spherical Bessel functions,

$$i2\pi \left[\frac{\hat{z}}{\hat{r}}\right] \{j_1(2\pi\hat{r}) - iy_1(2\pi\hat{r})\}.$$

The convolution integral is then

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-a^2\hat{r}^2}\; i2\pi \left[\frac{\hat{z}'}{\hat{r}'}\right] \{j_1(2\pi\hat{r}') - iy_1(2\pi\hat{r}')\}\, d\hat{x}\, d\hat{y},$$

where

$$\hat{r}^2 = \hat{x}^2 + \hat{y}^2$$

$$\hat{r}'^2 = (\hat{x}' - \hat{x})^2 + (\hat{y}' - \hat{y})^2 + \hat{z}'^2 \text{ , } \hat{z} = 0 \text{ .}$$

The variable $\hat{z}'$ is the distance along the z axis from the initial plane. Although the overall integral converges due to the Gaussian term, intermediate steps in the solution that involve integral representations may diverge depending on the nature of the argument and the order of the Bessel function concerned. This divergence problem can be avoided if the expression for $\hat{z}'$ is made complex after the manner of Kogelnik. This technique has proved useful and it appears that a series expansion solution to the diffraction integral does exist. Further study should reveal the amplitude and phase distributions in an unapproximated first-order description.

STUDENTS WHO EARNED A DEGREE UNDER THIS PROJECT

Barbara Tehan Landesman, MS (no thesis), 1984
PhD, expected completion 1985

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ION BEAM PROCESSING OF OPTICAL COATINGS ON PLASTICS

U. J. Gibson

BRIEF DESCRIPTION

This two-year project was a study of the use of argon ion bombardment during deposition to increase the abrasion resistance and adhesion of thin dielectric films deposited onto unheated substrates. The focus of the work was on the development of rugged antireflective (AR) coatings of magnesium fluoride (MgF_2).

SUMMARY OF RESULTS

The deposition of mechanically durable MgF_2 films onto unheated substrates was successfully demonstrated for the first time. The films deposited with concurrent ion bombardment showed comparable adhesion and abrasion-resistant performance to films deposited onto quartz substrates at 300 C (the normally required processing temperature for MgF_2). No excess visible absorption was introduced as a result of this process, making it an ideal solution to the difficult problem of applying rugged AR coatings to plastic and other temperature-sensitive substrates.

These coatings were then applied to plexiglass and polycarbonate substrates, and were compared to films deposited without bombardment. In both cases, mechanically durable films were produced, and in the case of polycarbonate, the films were shown to be more abrasion-resistant than the bare substrate. The microstructure and stoichiometry of these films were studied and linked to their mechanical and optical performance.

DESCRIPTION OF WORK DONE

This project encompassed the construction of the vacuum system used in the work, study of the deposition of conventional and ion-assisted deposition (IAD) films onto quartz

substrates, and the transfer of the techniques developed to the coating of plastic substrates. Four contributed papers at local, national, and international meetings, as well as two refereed journal articles, resulted from the work. Several commercial enterprises have expressed an interest in developing the technique.

A conventional diffusion-pumped system was assembled for the project from available equipment and a modest investment in needed parts. The system was equipped with a Kaufman-type ion source, a crystal monitor for deposition monitoring, and a thermal evaporation source.

The system was used initially for the deposition of films with conventional evaporation parameters to set a baseline of adhesion and abrasion-resistance performance against which to compare the films. Soft and hard standard films were made with unheated and 300 C quartz substrates, respectively. Films were then made using ion bombardment at a range of energies from 1 keV to 125 eV, with the current density varying from 0 to 55 $\mu A/cm^2$. It was determined that while the mechanical properties of the films were improved at all energies, the optical absorption increased noticeably above 300 eV. No lower threshold for the required bombardment energy has been encountered in the range available to us experimentally, with ion currents as low as 20 $\mu A/cm^2$. The abrasion resistance (eraser test) and adhesion (tape test) of the IAD films were comparable to, or better than, the hard standard deposited at high temperatures.

The process parameters developed for coating the quartz were then used for the coating of plastic substrates, which cannot tolerate the high temperatures used for conventional hard MgF_2 depositions. The ion beam processing led to durable films (in some cases more durable than the substrate itself), with AR properties. The ion bombardment of the film, and of the substrate for a precleaning effect, dramatically improved the adhesion of these films to the plastic substrates.

The films were also characterized optically, chemically, and microscopically using a spectrophotometer to measure the transmission, Rutherford backscattering spectrometry, a transmission electron microscope, and x-ray diffraction. Differences in the stoichiometry of the films could be correlated with the changes in their short-wavelength optical response, and the change in their microstructure with the changes in their mechanical performance. Briefly, a fluorine depletion, with some oxygen compensation, is responsible for a shift in the ultraviolet-absorption edge to slightly longer wavelengths in the IAD films. The ion bombardment has dramatic effects on the structure of the MgF_2, reducing the degree of crystallinity and the number of large crystallites. This is the opposite effect from that noted due to a heated substrate, which tends to increase the formation of large crystals. Thus the ion bombardment produces a dense, amorphous structure of the films, which results in improved mechanical properties. Further discussion of the results may be found in the papers published on this work.

PUBLICATIONS

1. C. M. Kennemore III, "Ion beam processing of ambient temperature optical coatings," paper presented at the 4th Annual Symposium of the Arizona Chapter of the American Vacuum Society, Tucson, Arizona, March 1-2, 1984.

2. C. M. Kennemore III and U. J. Gibson, "Ion beam processing for coating onto ambient temperature substrates," Optical Society of America Topical Meeting on Optical Interference Coatings, Monterey, California, April 17-19, 1984 and accepted for publication in Applied Optics.

3. U. J. Gibson and C. M. Kennemore III, "Ion-assisted deposition of MgF_2 at ambient temperatures." paper presented at the International Conference on Thin Films (ICTF-6), Stockholm, Sweden, August 13-17, 1984, and submitted for publication in Thin Solid Films.

OPTICAL COATINGS FOR THE X-RAY TO ULTRAVIOLET WAVELENGTH RANGE

C. M. Falco

BRIEF DESCRIPTION

The purpose of this research is to develop sputter epitaxy techniques for the production of high-reflectivity mirrors for near-normal incidence in the x-ray-ultraviolet (X-UV) wavelength range (10 to 300 Å).

SUMMARY OF RESULTS

The research completed during the first year of this contract has consisted of (1) implementation of several computer codes for X-UV multilayer mirror design, (2) acquisition of a data base of optical constants in this wavelength range, (3) theoretical designs of several mirrors for specific wavelengths in the X-UV range using the appropriate optical constants, (4) fabrication of several sets of mirrors on float glass and single-crystal silicon substrates, (5) structural characterization of these mirrors using high- and low-angle x-ray diffraction, as well as Rutherford backscattering spectroscopy, (6) initial testing of the reflectivity of these mirrors using the synchrotron source at the University of Paris, and (7) modeling of the results obtained by including the effects of interface-roughness and layer-thickness uncertainties.

DESCRIPTION OF WORK DONE

Several computer programs for calculating the reflectivity of multilayer coatings as a function of wavelength and incidence angle, with and without interfacial roughness, have been implemented. Using these programs, theoretical results in the literature were reproduced for the soft x-ray reflectivity of carbon/tungsten multilayer mirrors, thus demonstrating the correct functioning of the programs.

A computer data base was assembled, consisting of a complete set of optical constants (real and imaginary parts) for all elements from Z = 1 to 94 and for wavelengths between 6 and 124 Å. Data were obtained from a compilation by Henke et al.[1] A literature search was also continued to widen the data base over a broader range of wavelengths, and to include compounds as well as elemental materials. During the next year data will be added for (1) magnesium, aluminum, copper, silver, gold, bismuth, carbon, and aluminum oxide from the near uv down to ∿0.1 Å,[2] and (2) transition and noble metals, the lanthanides, and actinides from the near uv down to ∿6 Å.[3] The addition of these data will allow calculations to be performed over the entire X-UV-wavelength region of interest, using optical constants for most practical materials. However, it should be noted that the distribution and accuracy of available data for the uv-soft x-ray region of the spectrum is uneven, and for some regions of interest the values of the optical constants must be obtained by interpolation or extrapolation of different data sets. Thus it is important to update the data base continuously.

The effect of small variations in the design parameters on the calculated reflectance characteristics was investigated. For this work an aluminum/nickel multilayer mirror designed for maximum reflectivity at 300 Å was used. For a "perfect" multilayer mirror, with no interface roughness or variations in the layer thickness throughout the material, the relevant parameters that affect the maximum reflectance are the total number of periods in the multilayer and the relative ratio of the aluminum layer thickness to that of the nickel. It was found that the maximum reflectance first increased rapidly with increasing numbers of layers and finally saturated. When the relative ratios of the two layer thicknesses were changed ("beta" parameter), a fairly broad maximum in the reflectance vs beta was found. The full width, at half maximum of the reflectance vs wavelength, was fairly constant over a wide range of beta and finally increased rapidly. The maximum reflectance changed by a

factor of two for this range of beta. Thus it is desirable to keep beta small for high-resolution mirrors and large for a wider passband.

The effect of variations in the deposition parameters on the calculated reflectance of several mirrors was also calculated. The deposition process in our sputtering system is well controlled, with variations limited to ∿0.3% by active feedback control. However, it is important to determine how sensitive the reflectance of mirrors in this wavelength range is to long-term variations in the deposition rate ("drift"), short-term variations, and variations in the relative-layer thicknesses. It was found that the calculated effects on the reflectance from each of these sources, assuming reasonable values for control, were negligible.

Prior to deposition of the first samples, several such multilayer mirrors operating in the wavelength range of 10 to 300 Å were designed (as shown in the table below). For each of these designs the reflectivity vs wavelength was calculated at the desired angle of incidence (where 90° denotes incidence normal to the mirror, and 0° is grazing incidence), as well as the reflectivity vs angle of incidence assuming x rays of 1.54-Å wavelength. The latter was done so that the calculated results could be compared with measuered standard θ to 2θ Bragg x-ray diffraction curves obtained using copper radiation.

Mirror Designs

Materials (layer thicknesses) (Ångstroms)	Center wavelength (Ångstroms)	Angle of incidence (degrees)	Maximum reflectance (percent)
W/C (6.5/6.85)	13	60	2.9
W/C (8/25.75)	48	45	22.0
Cr/C (13.5/36.4)	57	35	30.0
W/C (16/34)	100	90	10.0
Al/Nb (127.25/32.61)	300	90	34.0

Figure 1 shows the calculated reflectance vs wavelength, and Fig. 2 shows the calculated low-angle diffraction characteristic for 1.54 Å x rays from a carbon/tungsten mirror designed to operate at normal incidence with maximum reflectance at 100 Å. The interest in low-angle x-ray diffraction characteristics is due to the fact that these measurements can be obtained in available laboratory facilities to characterize the samples, while the reflectivity vs wavelength measurements must be done in collaboration with personnel at an appropriate synchrotron radiation facility.

Mirrors of the above designs were fabricated in June in collaboration with a visiting professor in our laboratory, Dr. Bernard Vidal of the University of Marseilles, using the university microprocessor-controlled sputtering system. Preliminary Bragg diffraction characterization of these samples was carried out and the samples were then shipped to the synchrotron at L.U.R.E., University of Paris, for measurements in collaboration with Dr. Pierre Dhez. Unfortunately, equipment difficulties have prevented measurement of the reflectance of these mirrors as yet. In addition to the synchrotron measurements, low-angle diffraction measurements using 1.54 Å x rays were undertaken in collaboration with Dr. Bernard Vidal. Results from the carbon/tungsten mirror designed for 100 Å are shown in Fig. 3. In principle, it should be possible to use these results to learn about any defects in the deposition process (incorrect layer thicknesses, interface roughness, etc.), as well as to calculate the expected reflectivity of the actual mirror. Rutherford backscattering spectroscopy measurements were also done on this sample to determine the actual composition of the film.

To summarize the conclusions from the various measurements on the first X-UV multilayer mirrors during the initial year of this research: (1) The calibration of the carbon sputtering rate was in error by a factor of 4. Therefore far less carbon than desired was

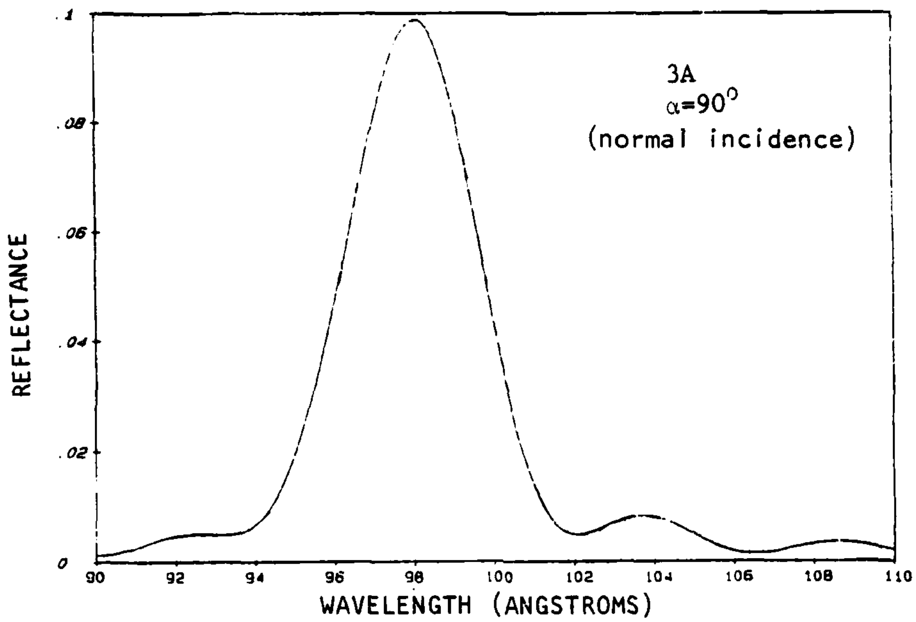

Figure 1. Theoretical reflectance vs wavelength for a carbon/tungsten multilayer mirror designed to operate at 100 Å.

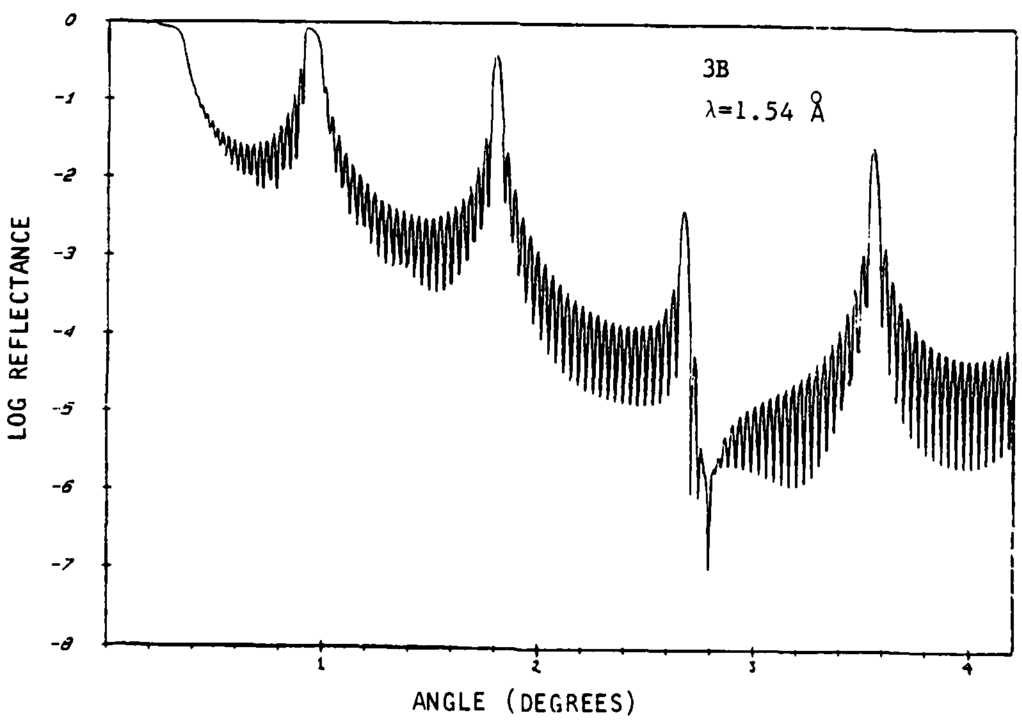

Figure 2. Theoretical reflectance vs grazing angle for 1.54-Å x rays from a carbon/tungsten multilayer mirror designed to operate at a wavelength of 100 Å.

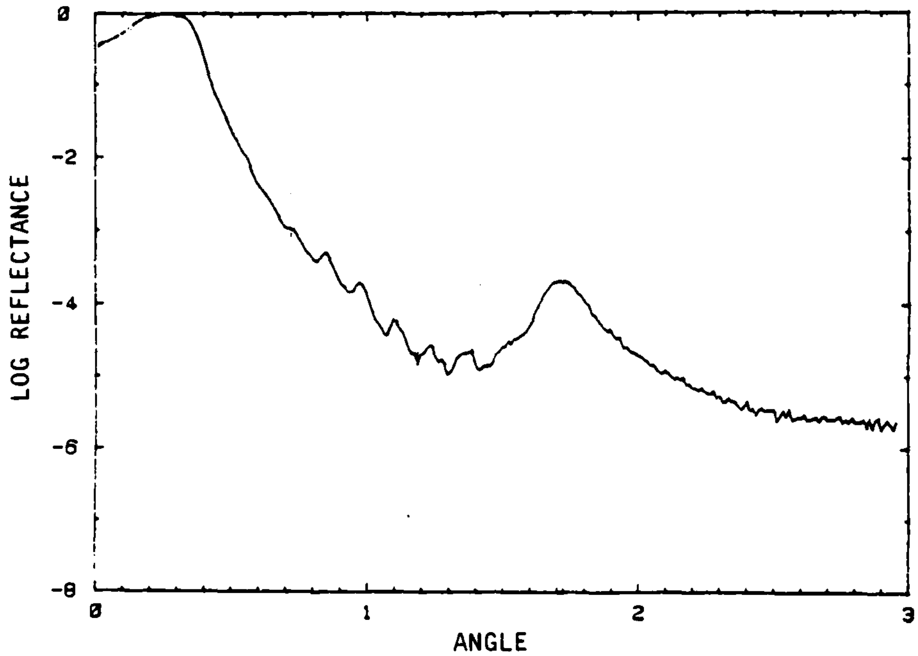

Figure 3. Measured reflectance vs grazing angle for 1.54-Å x rays from a carbon/tungsten multilayer mirror designed to operate with maximum reflectance at 100 Å. Due to calibration error, the thickness of the carbon layers was a factor of 4 smaller than assumed for the design.

deposited. This considerably decreased the Bragg reflectance maxima. (2) Comparison of theoretical and experimental low-angle x-ray diffraction measurements indicates that during deposition of the 27th or 29th layer (carbon), malfunction of the carbon sputtering gun occurred, effectively preventing deposition of that layer. (3) According to model calculations, interfacial roughness could have reduced the low-angle reflectance by as much as an order of magnitude. Interdiffusion at the interfaces could also contribute to this reduction of the reflectance.

Based on the considerable theoretical and experimental progress made in the first year of research on preparation of multilayer X-UV mirrors and modeling of their performance, the efforts in the next year will be directed toward production and characterization of mirrors operating at wavelengths ∿300 Å and ∿12 Å.

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APPENDIX A
JSOP PROJECTS

1st Year	
Turner	Evaporated Thin Film Lens
Burke	Interferometric Measurements
Franken/Bogatin	Electromagnetic Anisotropy Hollow-Anode-Cathode Discharges
Burke/Boreman	Coupling of Beams
Hopf	Second Harmonic Interferometers
Scully	Heterodyne Photodetection
Sargent/ Shoemaker	Optical Bistability and Phase Conjugation
Scully/Small	Ring Laser Interferometry
Meinel	Thin Films Under High Radiant Fluxes
Wolfe/Shack	Surface and Volume Scattering
Jacobs	Magnetostriction/Thermal Expansion
Lamb	Atoms in Very Intense Laser Fields
Barrett	Optical Communications

Second Year	
Burke	Dispersion in Fiber Waveguides
Hopf	Second-Harmonic Interferometers
Sarid/Burke	Waveguide Prism Coupling
Stegeman	Brillouin Scattering
Meinel	Properties of Metal Glasses
Wolfe	Experimental Scattering Studies
Gibbs	Optical Stability
Gibbs	ARO Bistability
Wyant	BSO Crystal for Real Time Contouring
Lamb	Quantum Theory of Optical Communications

Third through Fifth Years	
Macleod	Use of Surface Electromagnetic Waves in Thin-Film Measurement
Burke	Measuring the Dispersion and Polarization Characteristics of Ultra-Broadband Optical Fibers
Hopf	Convolution-Product Interferometers Using Second Harmonic Generation
Sarid	Long Lifetime Surface Plasmons
Stegeman	Nonlinear Guided Wave Interactions
Sargent	Effects of Transverse Variations on Optical Bistability
Dereniak	Evaluation of the Flashing Effect on Indium Antimonide Detectors
Meinel	Exploration of Optimization Strategies Applicable to a Large Segmented Spherical Primary Mirror with Aspheric Relay Optics
Wolfe	The Characterization of Optical Surfaces
Gibbs	Optical Bistability
Gibbs	ARO Bistability
Lamb	Atoms in Very Intense Laser Fields
Seraphin	Modulated Emittance Spectroscopy
Koliopoulos	Wavefront Sensing
Shack	Aberrated Gaussian Beams
Gibson	Ion Beam Processing

APPENDIX B
DEGREES AWARDED TO STUDENTS RECEIVING JSOP SUPPORT

Eric Bogatin, PhD, 1980. "Three New High Precision Tests of Relativity and Mach's Principle."

William Bomberger, PhD, 1980. "Interferometric Measurement of Dispersion."

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Stephen Browning, PhD, 1983. "Electron Bombardment of Certain Thin Films During Deposition."

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Alan Craig, PhD, 1984. "Surface Plasmon Waves on Thin Metal Films."

Janet Fender, PhD, 1981. "An Investigation of Computer-Assisted Stray Radiation Analysis Programs."

Tao-Yi Fu, PhD, 1984. "Information Transfer Efficiency of X-Ray Image Intensifier-Based Imaging Systems."

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